Finding the Higgs boson

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Maria Laach School

Lecture 3

- Properties of the Higgs boson
  - Theoretical uncertainties & motivations for precision measurements
- Higgs production at the Tevatron and LHC
  - Discovery vs spectroscopy
- Introduction to SUSY Higgs

Review of Higgs Couplings

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

$$L = -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)h$$

v=246 GeV

  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos
- Higgs couples to gauge boson masses

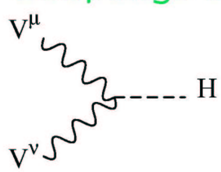
$$L = gM_W W^{+\mu}W_\mu^{-}h + \frac{gM_Z}{\cos\theta_W}Z^\mu Z_\mu h + \ldots.$$

$$g^2 = \frac{G_F}{\sqrt{2}}8M_W^2 = \frac{e^2}{\sin^2\theta_W} = \frac{4\pi\alpha}{\sin^2\theta_W}$$

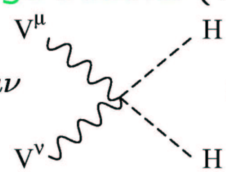
- Only free parameter is Higgs mass!
- Everything is calculable….***testable theory***

Review of Higgs Boson Feynman Rules

- Couplings to EW gauge bosons $(V = W, Z)$:

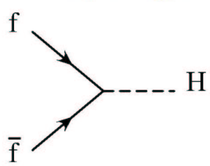


$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$



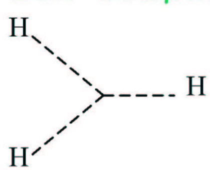
$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

- Couplings to fermions $(f = l, q)$:

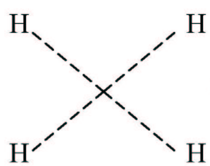


$$= -i\frac{m_f}{v}$$

- Self-couplings:



$$= -3i\frac{M_H^2}{v}$$

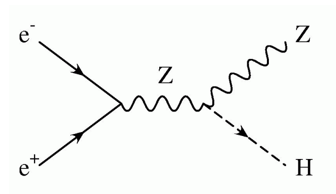


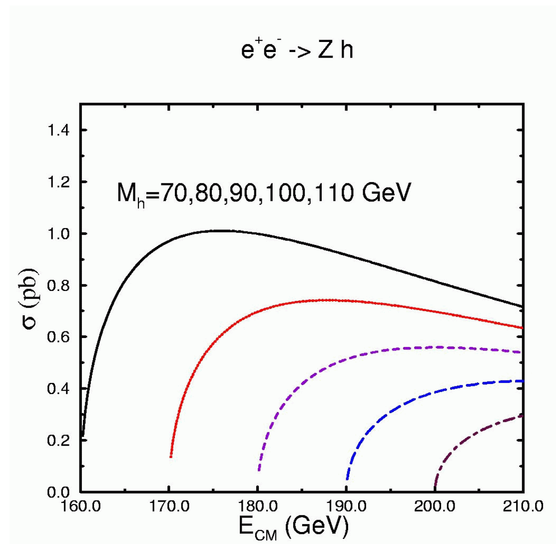
$$= -3i\frac{M_H^2}{v^2}$$

- Higgs couples to heavy particles
- ***No tree level coupling to photons (γ) or gluons (g)***
- $M_h^2 = 2v^2\lambda \Rightarrow$ large M_h is strong coupling regime
  - M_h is parameter which separates perturbative/non-perturbative regimes

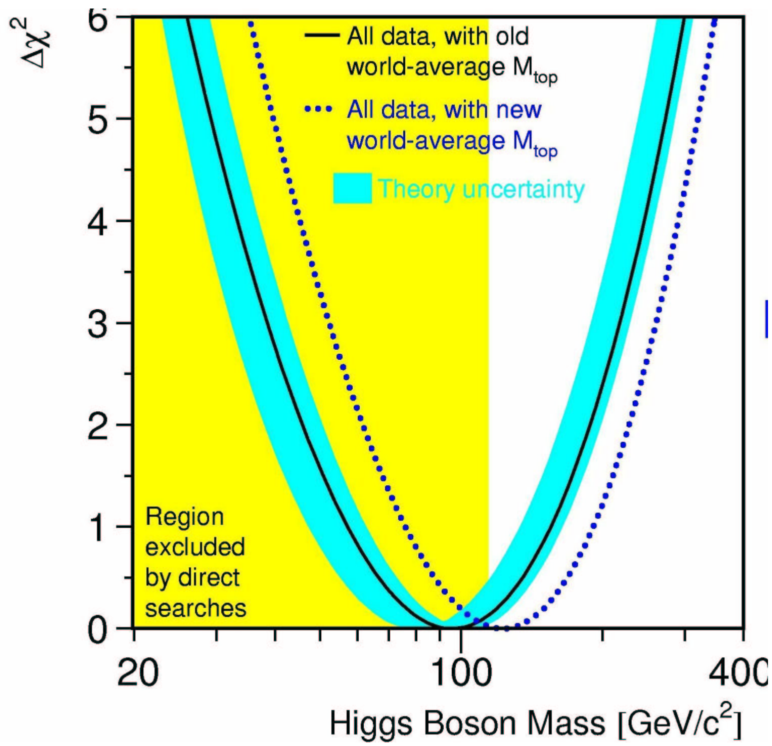
Higgs Searches at LEP2

- LEP2 searched for $e^+e^- \rightarrow Zh$
- Rate turns on rapidly after threshold, peaks just above threshold, $\sigma \sim \beta^3/s$
- Measure recoil mass of Higgs; ***result independent of Higgs decay pattern***
  - $P_{e-} = \sqrt{s}/2(1,0,0,1)$
  - $P_{e+} = \sqrt{s}/2(1,0,0,-1)$
  - $P_Z = (E_Z, \vec{p}_Z)$
- Momentum conservation:
  - $(P_{e-} + P_{e+} - P_Z)^2 = P_h^2 = M_h^2$
  - $s - 2\sqrt{s}\, E_Z + M_Z^2 = M_h^2$
- LEP2 limit, ***$M_h > 114.1$ GeV***





Precision measurements limit Higgs Mass



- Last year:
  - M_t=174±5.1 GeV
  - M_h=96^{+60}_{-38} GeV
  - M_h < 219 (95% cl)
- This year:
  - M_t=178±4.3 GeV
  - M_h=117^{+67}_{-45} GeV
  - M_h < 251 (95% cl)

Best fit not in region excluded from direct searches

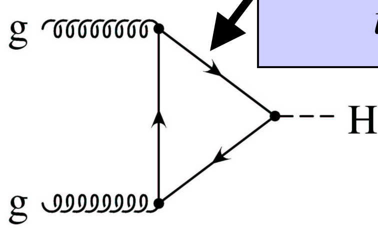
Higgs production at Hadron Colliders

- Many possible production mechanisms; Importance depends on:
  - Size of production cross section
  - Size of branching ratios to observable channels
  - Size of background
- Importance varies with Higgs mass
- Need to see more than one channel to establish Higgs properties and verify that it is a Higgs boson

Production Mechanisms in Hadron Colliders

- Gluon fusion
  - Largest rate for all M_h at LHC
  - Gluon-gluon initial state
  - Sensitive to top quark Yukawa λ_t

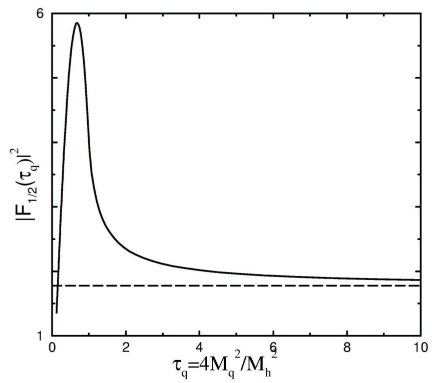
Largest contribution is top loop



- Lowest order cross section:

$$\hat{\sigma}_0(gg \to h) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2} \left| \sum_q F_{1/2}(\tau_q) \right|^2 \delta(M_h^{\,2} - \hat{s})$$

  - $\tau_q = 4M_q^2/M_h^2$
  - Light Quarks: $F_{1/2} \to (M_b/M_h)^2 \log(M_b/M_h)$
  - Heavy Quarks: $F_{1/2} \to -4/3$



Rapid approach to heavy quark limit

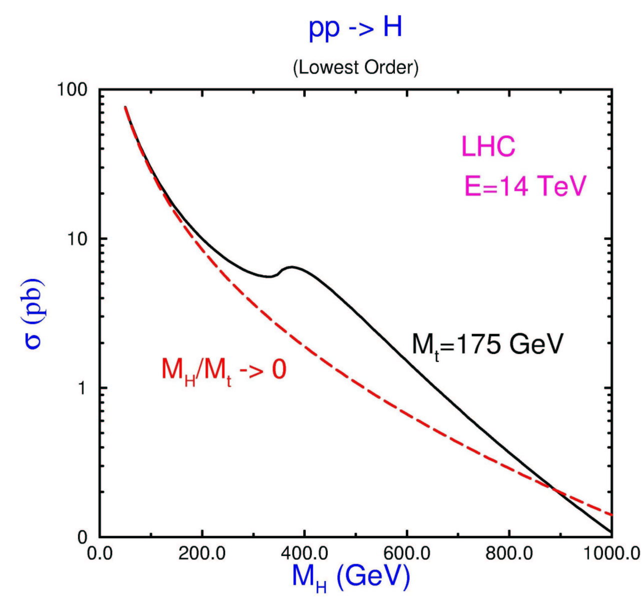
In SM, b-quark loops unimportant

Gluon fusion, continued

- Integrate parton level cross section with gluon parton distribution functions

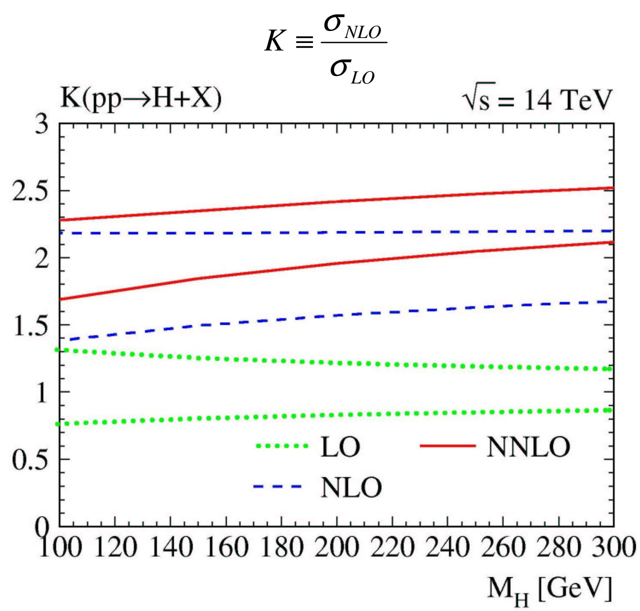
$$\boxed{\sigma_0(pp \to h) = \hat{\sigma}_0 z \int_z^1 \frac{dx}{x} g(x, \mu_F) g(\frac{z}{x}, \mu_F)}$$

  - $z = M_h^2/S$, S is hadronic center of mass energy
- Rate depends on μ_R, μ_F
- Rate for gluon fusion independent of M_t for $M_t >> M_h$
  - Counts number of heavy fermions
- Effective Lagrangian used to compute QCD corrections to NNLO
  - Simplifies calculation by reducing number of loops by one
  - Large M_t calculation accurate at NLO when rescaled by LO with mass dependence



$$\boxed{L = -\frac{\alpha_s}{3\pi v} G_{\mu\nu} G^{\mu\nu} H}$$

NNLO, $gg \to h$



NLO&NNLO results allow improved estimates of theoretical uncertainties

Rates depend on renormalization scale, $\alpha_s(\mu_R)$, and factorization scale, $g(\mu_F)$

Bands show $.5M_h < \mu < 2\ M_h$

LO and NLO μ dependence bands don't overlap

μ Dependence used as estimate of theoretical uncertainty

Higher order corrections computed in large M_t limit

Harlander & Kilgore

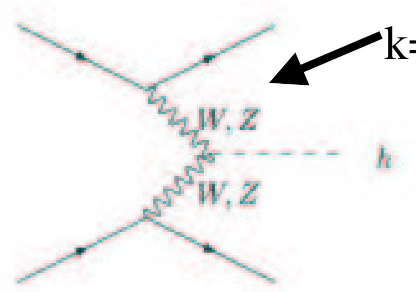
Vector Boson Fusion

- $W^+W^- \to X$ is a real process: $\sigma_{pp\to WW\to X}(s) = \int dz \left.\frac{dL}{dz}\right|_{pp/WW} \sigma_{WW\to X}(zs)$
- Rate increases at large s: $\sigma \approx (1/M_W^2)\log(s/M_W^2)$
- Integral of cross section over final state phase space has contribution from W boson propagator:

$$\int \frac{d\theta}{(k^2 - M_W^2)^2} \approx \int \frac{d\theta}{(2EE'(1-\cos\theta) + M_W^2)^2}$$

Peaks at small θ

- Outgoing jets are mostly forward and can be tagged



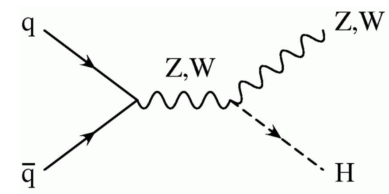
k=W,Z momentum

Idea: Look for h decaying to several different channels

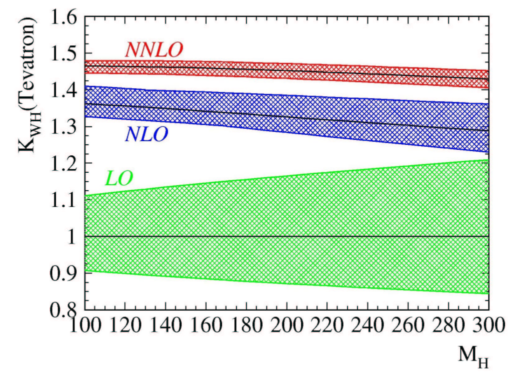
Ratio of decay rates will have smaller systematic errors

W(Z)-strahlung

- W(Z)-strahlung ($q\bar{q}\rightarrow$Wh, Zh) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to ***weak*** coupling
  - Below 130-140 GeV, look for $q\bar{q} \rightarrow Vh, h \rightarrow b\bar{b}$
  - For M_h>140 GeV, look for $h\rightarrow W^+W^-$
- Theoretically very clean channel
  - NNLO QCD corrections: $K_{QCD}\approx 1.3$-1.4
  - Electroweak corrections known (-5%)
  - Small scale dependence (3-5%)
  - Small PDF uncertainties



Improved scale dependence at NNLO



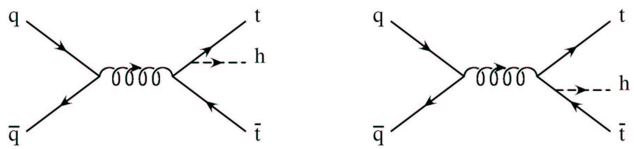
Brein, Djouadi, Harlander, hep-ph/0307206

$t\bar{t}h$ Production

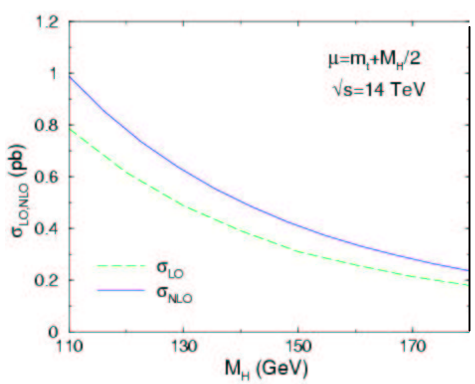
•tth production unique channel to measure top quark Yukawa coupling

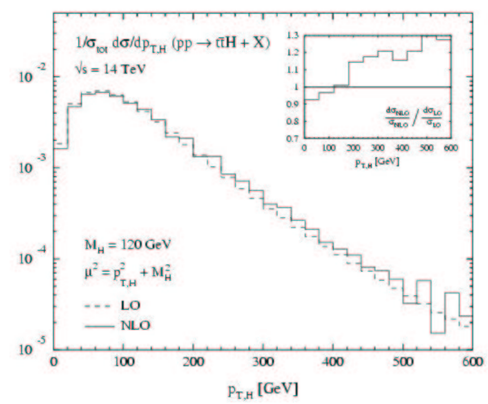
–h→tt never important

•bbh small in SM, but can be enhanced in SUSY models with large tan β



- Large QCD effects



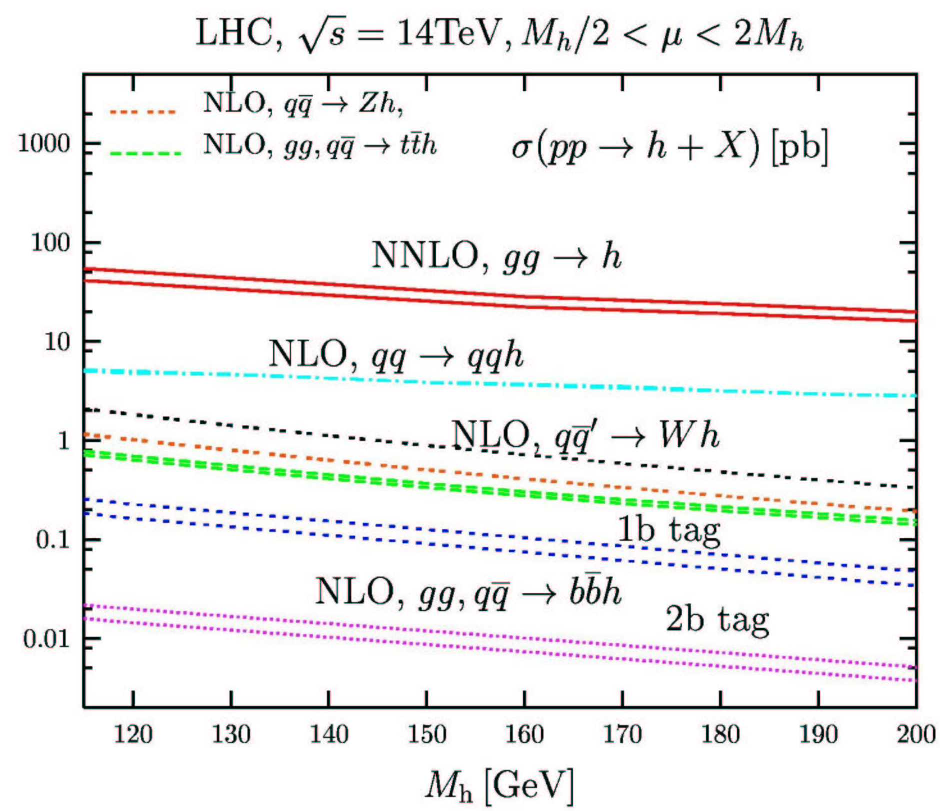


QCD effects not only change normalization, they change shape of distributions

Dawson, Jackson,Reina, Orr, Wackeroth

Beenacker, Dittmaier, Kramer, Plumper, Spira, Zerwas

Comparison of production mechanisms at LHC



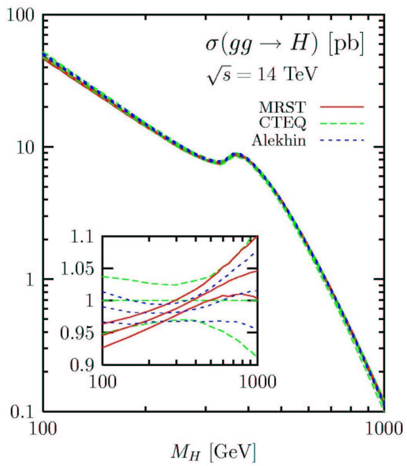
Bands show scale dependence

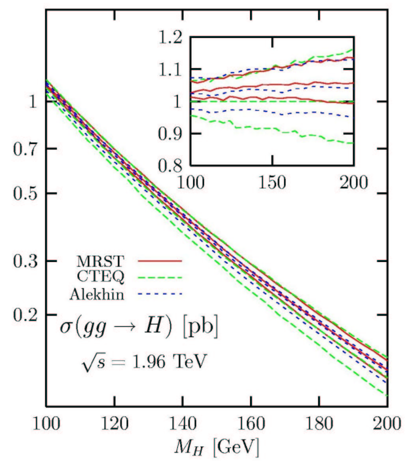
All important channels calculated to NLO or NNLO

Importance of higher order corrections

- QCD effects can be large
- Leading order cross sections have large uncertainties due to:
  - Renormalization/factorization scale dependence
  - Uncertainties from parton distribution functions (PDFs)
- Differential cross sections very sensitive to higher order QCD corrections
- Important modes have large QCD backgrounds
  - Often backgrounds only known to leading order

PDF uncertainties



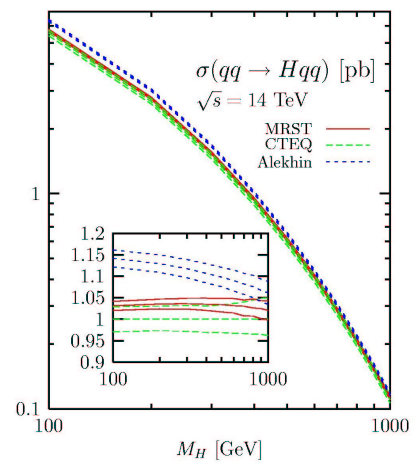


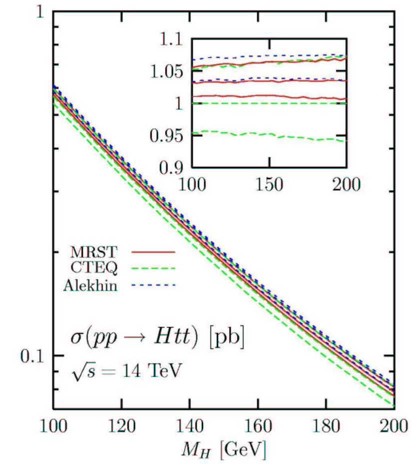
CTEQ6m: 40 PDFs for uncertainty studies

http://user.pa.msu.edu/wkt/cteq/cteq6pdf.html

NLO PDFs with NLO cross sections!

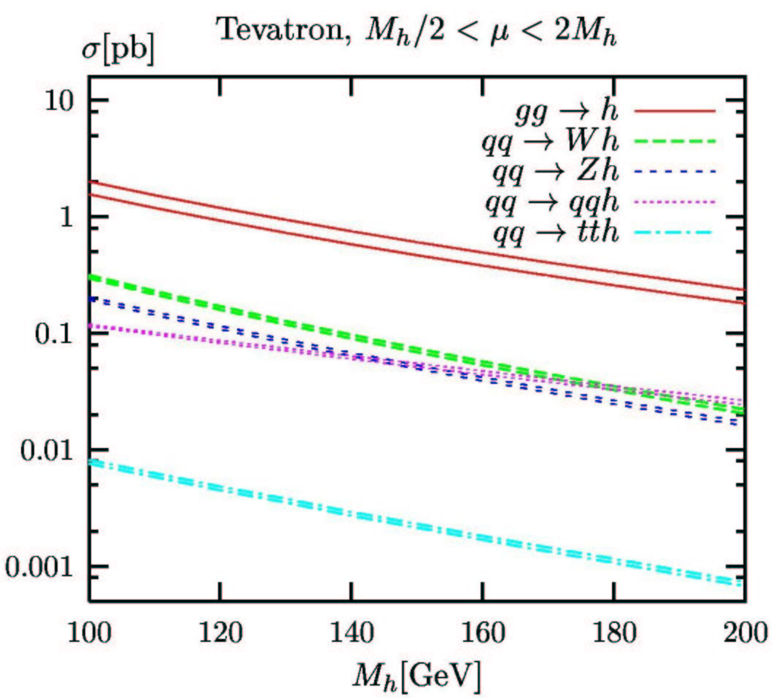
Djouadi & Ferrag, hep-ph/0310209





Smaller PDF uncertainties in vector boson fusion ($q\overline{q}$ initial channel)

Comparison of rates at Tevatron

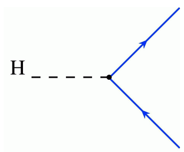


NNLO or NLO rates

- Luminosity goals for Tevatron: 4-6 fb^{-1}
- Higgs very, very hard at Tevatron

Higgs Decays

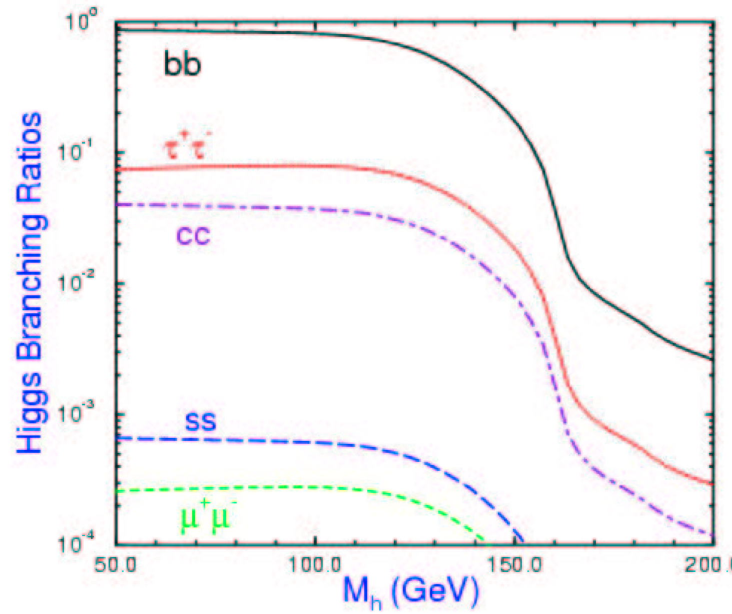
- $h \rightarrow f\bar{f}$ proportional to m_f^2



$$\frac{BR(h \rightarrow b\bar{b})}{BR(h \rightarrow \tau^+\tau^-)} = N_c \left(\frac{m_b^{\ 2}}{m_\tau^{\ 2}}\right)\left(\frac{\beta_b}{\beta_\tau}\right)^3$$

$$\beta_f = \sqrt{1 - \frac{4m_f^{\ 2}}{M_h^{\ 2}}}$$

- β^3 typical of scalar (pseudo-scalar decay $\approx\beta$)
- Identifying b quarks very important for Higgs searches

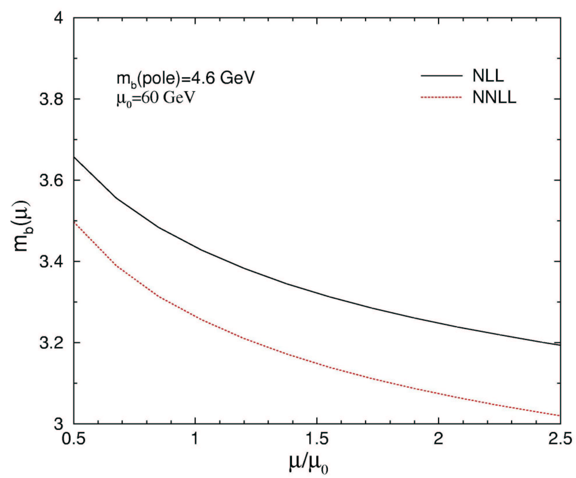


For $M_h < 2M_W$, decays to $b\bar{b}$ most important

QCD Corrections to $h \rightarrow Q\overline{Q}$

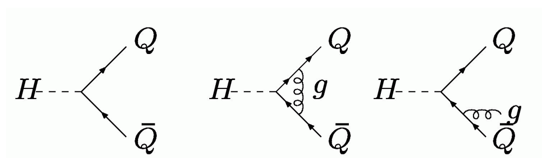
The heavier the Higgs, the larger its width

- Tree level: $\Gamma(h \rightarrow Q\overline{Q})_{tree} = \frac{3G_F M_h}{4\sqrt{2}\pi} M_Q{}^2 \beta_Q{}^3$
- Add QCD: $\Gamma(h \rightarrow Q\overline{Q})_{QCD} = \frac{3G_F M_h}{4\sqrt{2}\pi} \overline{m}_Q{}^2(M_h)\beta_Q{}^3 \left(1 + 5.67\frac{\alpha_s(M_h)}{\pi} + \ldots\right)$
- Large logs absorbed into running $\overline{\text{MS}}$ mass: $m_b(\mu^2) = m_b(m_b{}^2)\left(\frac{\alpha_s(m_b^2)}{\alpha_s(\mu^2)}\right)^{-12/23}$



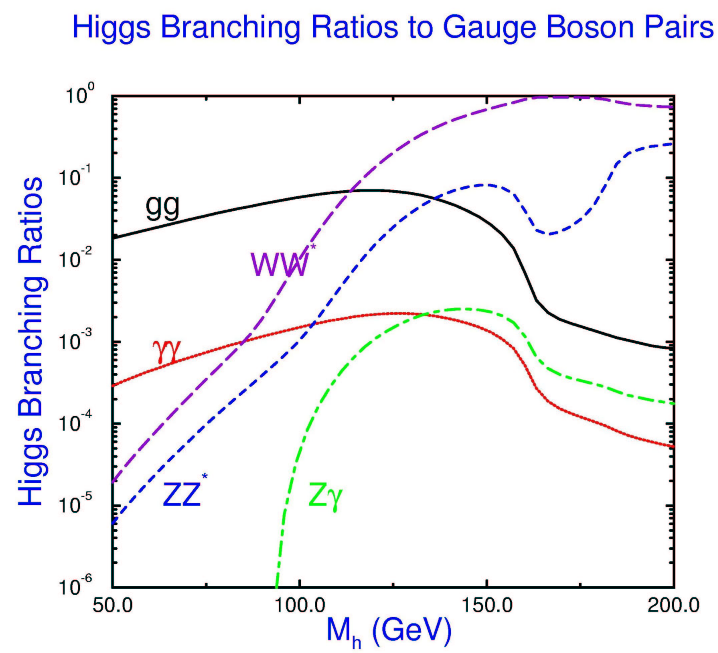
Effect of running m_b numerically important

➢ Virtual + real corrections



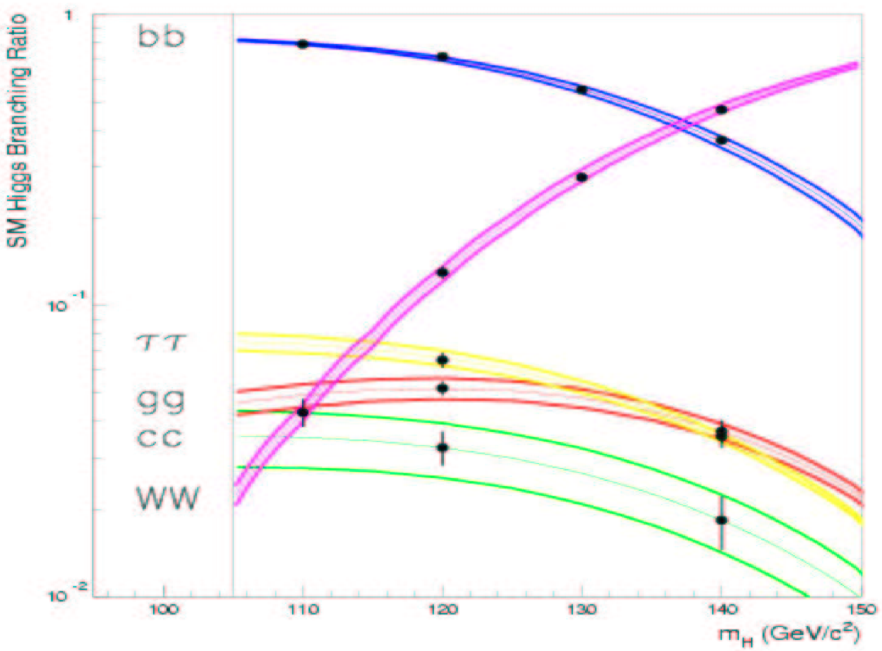
Higgs decays to gauge bosons

- $h \rightarrow gg$ sensitive to top loops
  - Remember no coupling at tree level
- $h \rightarrow \gamma\gamma$ sensitive to W loops, only small contribution from top loops
- $h \rightarrow W^+W^- \rightarrow f\bar{f}f\bar{f}$ has sharp threshold at 2 M_W, but large branching ratio even for M_h=130 GeV



For any given M_h, not all decay modes accessible

Status of Theory for Higgs BRs



- **Bands show theory errors**
- **Largest source of uncertainty is b quark mass**

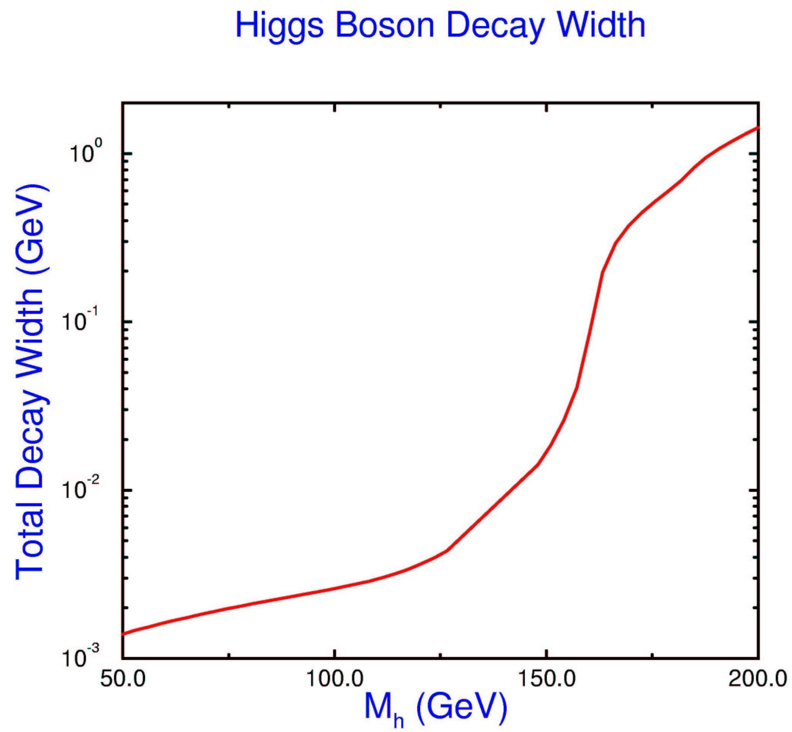
Data points are e^+e^- LC at $\sqrt{s}$=350 GeV with L=500 fb^{-1}

Battaglia & Desch, hep-ph/0101165

Total Higgs Width

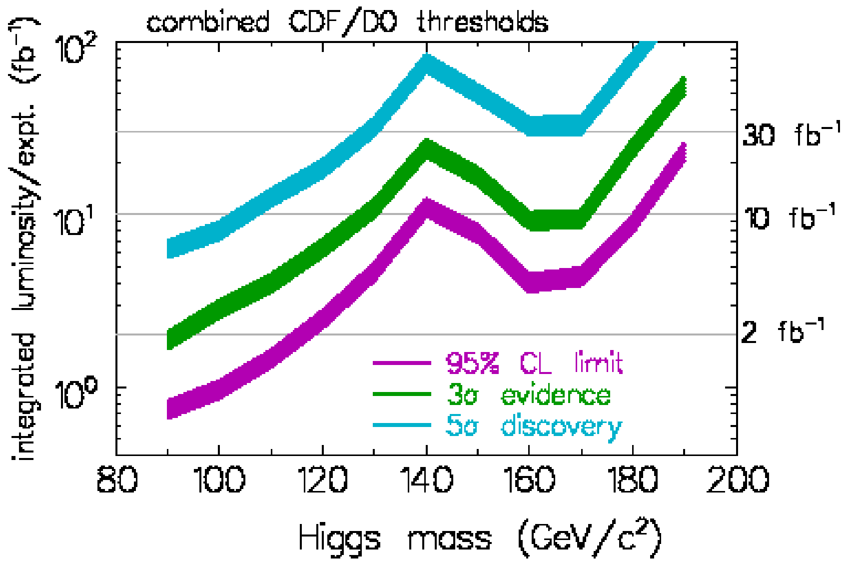
- Total width sensitive function of M_h
- Small M_h, Higgs is narrower than detector resolution
- As M_h becomes large, width also increases
  - No clear resonance
  - For M_h ~1.4 TeV, Γ_{tot} ~M_h

$$\boxed{\begin{aligned}\Gamma(h \to W^+W^-) &\approx \frac{\alpha}{16\sin^2\theta_W}\frac{M_h{}^3}{M_W{}^2}\\ &\approx 330 GeV\left(\frac{M_h}{1TeV}\right)^3\end{aligned}}$$



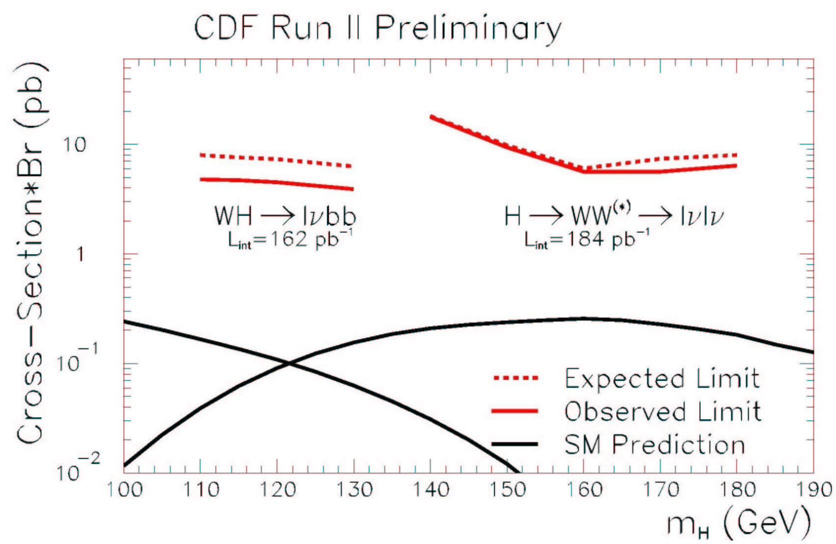
- *Higgs branching ratios easily computed with HDECAY program to NLO*
- *http://mspira.home.cern.ch/mspira/proglist.html*

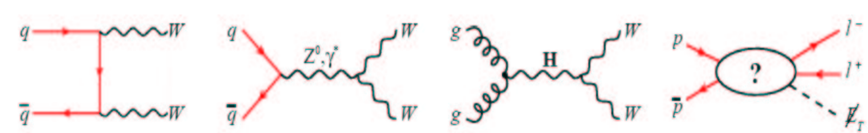
Higgs at the Tevatron



Current luminosity goals 4-6 fb^{-1}

- *Look for gg$\rightarrow$h; h$\rightarrow$WW*
- *Important for M_h>140 GeV*





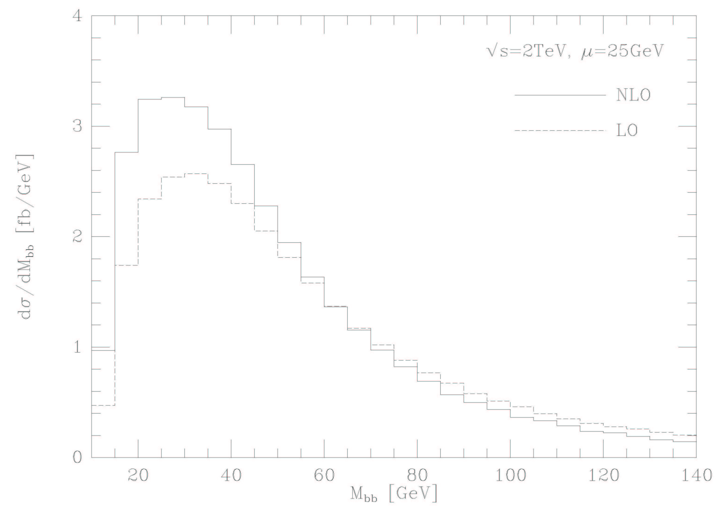
- Largest rate is gg$\rightarrow$h
- h $\rightarrow$b$\bar{b}$ has large QCD background

Higgs at the Tevatron, 2

- Wh, Zh production important for M_h<140 GeV, $h \rightarrow b\bar{b}$
- Background from $Wb\bar{b}$, $Zb\bar{b}$
- One of the few examples where both signal and background known to NLO

Wh, Zh and background in MCFM Monte Carlo to NLO

http:mcfm.fnal.gov



NLO corrections change shape of background

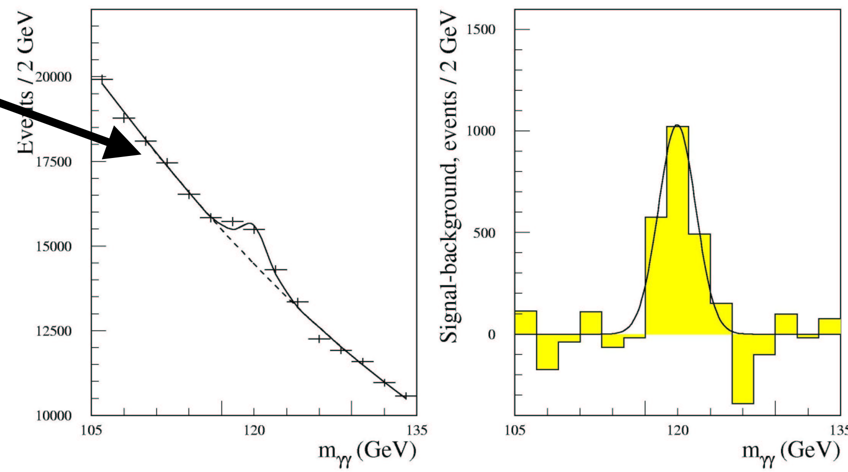
Ellis & Veseli, hep-ph/9810489

Search Channels at the LHC

$gg \rightarrow h \rightarrow b\bar{b}$ has huge QCD bkd:
Must use rare decay modes of h

- ***$gg \rightarrow h \rightarrow \gamma\gamma$***
  - Small BR ($10^{-3} - 10^{-4}$)
  - Only measurable for $M_h < 140$ GeV
- Largest Background: QCD continuum production of $\gamma\gamma$
- Also from γ-jet production, with jet faking γ, or fragmenting to π^0
- Fit background from sidebands of data

M_h=120 GeV; L=100 fb^{-1}

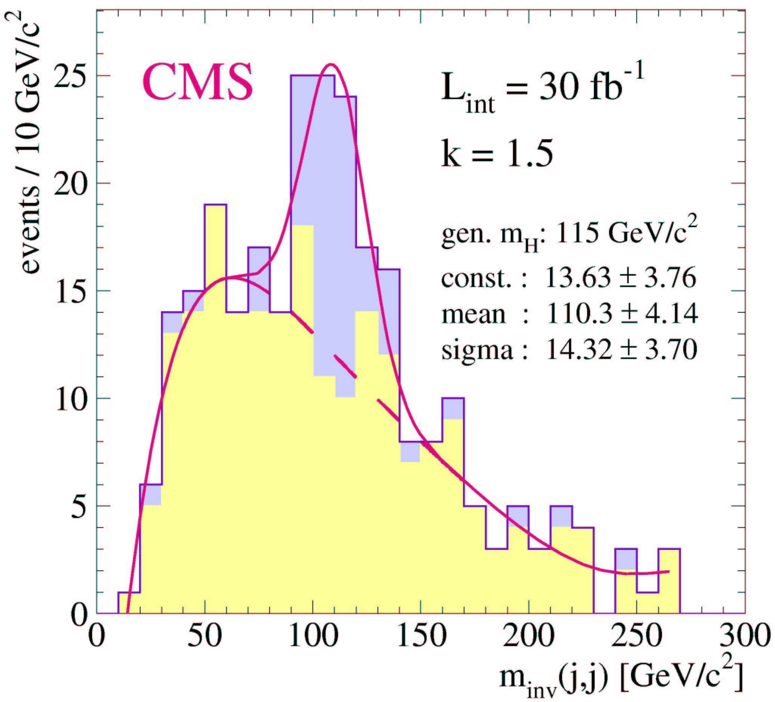


$S/\sqrt{B} = 2.8$ to $4.3\ \sigma$

$t\bar{t}h$ at the LHC: Important discovery channel

- ***$gg \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$***
- Spectacular signal
  - $t \rightarrow Wb$
  - Look for 4 b jets, 2 jets, 1 lepton

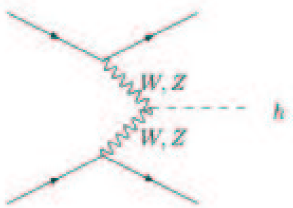
Unique way to measure top quark Yukawa coupling



Vector Boson Fusion for light Higgs

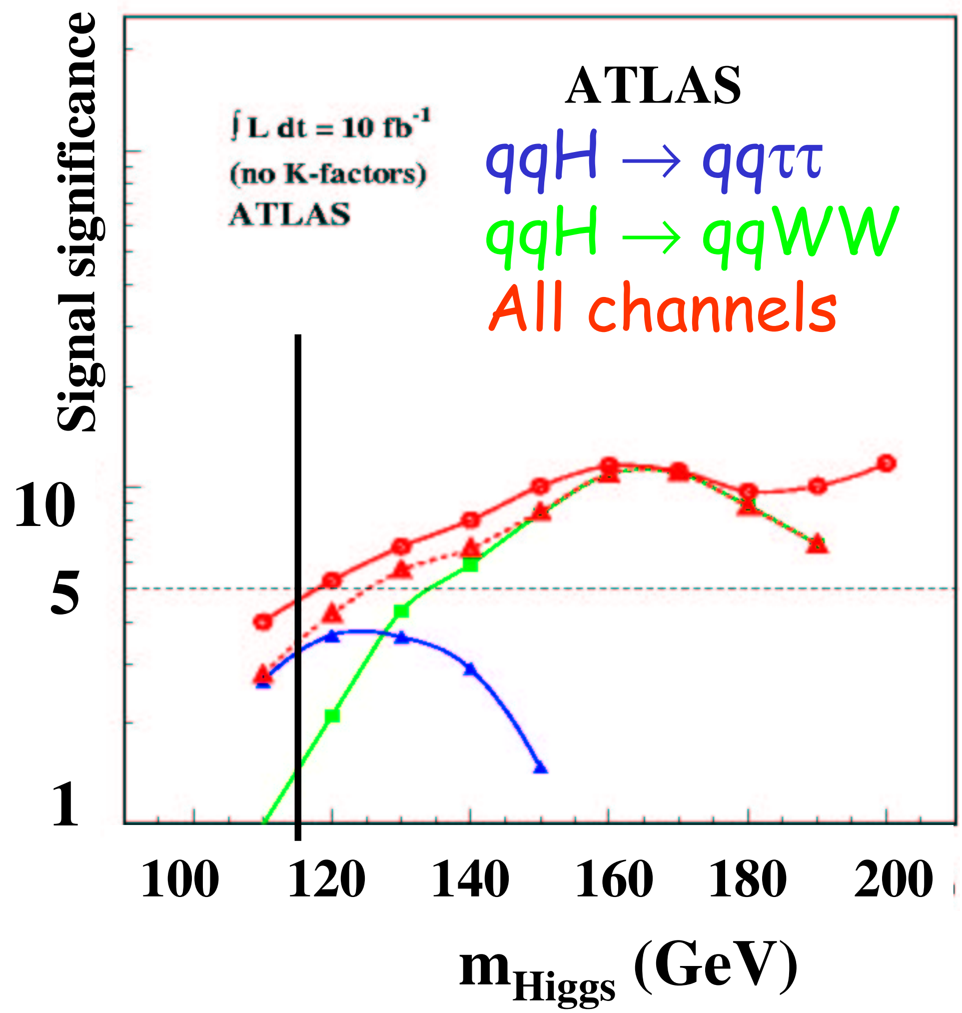
- For $M_h = 115$ GeV combined significance ~ 5σ

Vector boson fusion effective for measuring Higgs couplings



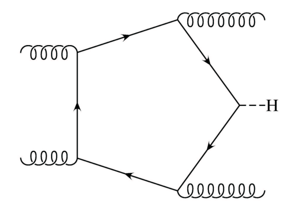
- Proportional to g_{WWh} and g_{ZZh}
- Often assume they are in SU(2) ratio:

$g_{WWh}/g_{ZZh} = \cos^2\theta_W$



Vector Boson Fusion

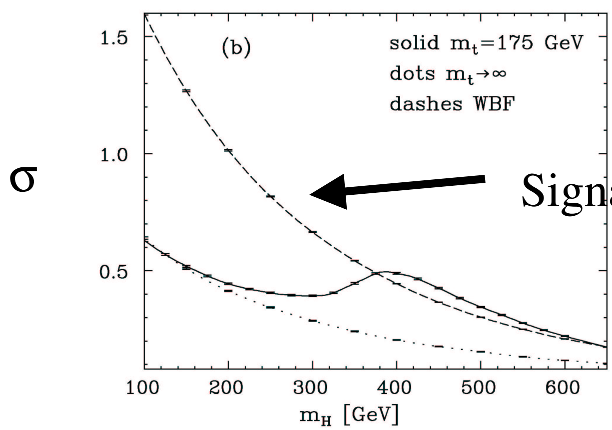
- Identify signal with forward jet tagging and central jet veto
- Large Higgs + 2 jet background from gg→ggh
- Kinematic cuts effective at identifying signal



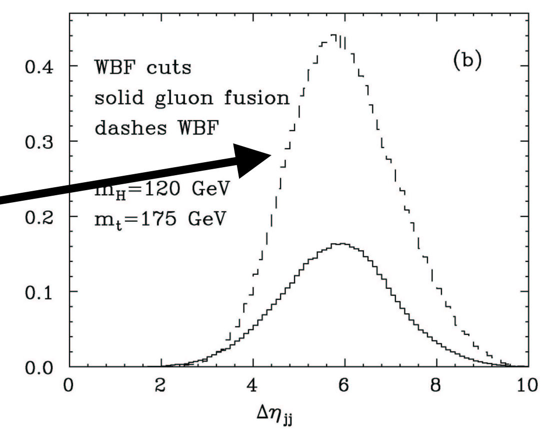
Proportional to g_{tth}

Higgs + 2 jet Production

Rapidity between outgoing jets



Signal from WBF after cuts



delDuca, Kilgore, Oleari, Schmidt, Zeppenfeld, hep-ph/0108030

Vector boson fusion for Heavy Higgs

Gold-plated

200 GeV < M_h < 600 GeV:

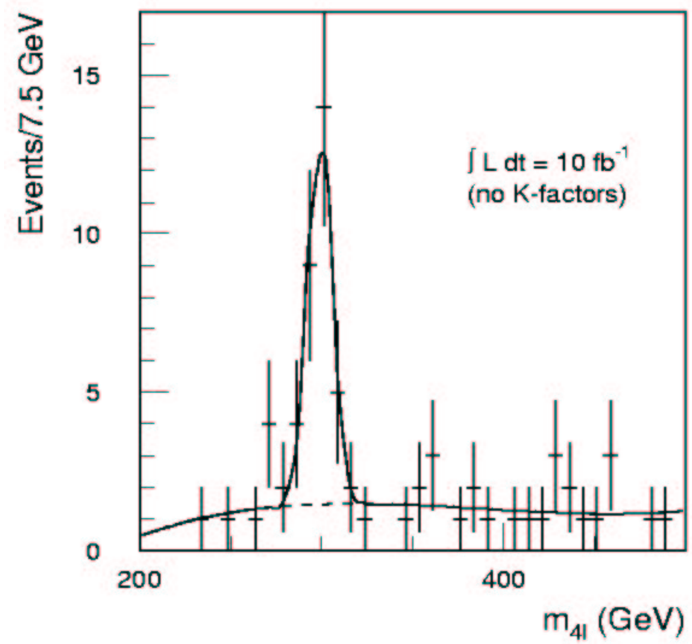
- discovery in $h \rightarrow ZZ \rightarrow l^+l^- l^+l^-$

•Background smaller than signal

•Higgs width larger than experimental resolution **(M_h > 300 GeV)**

- confirmation in $h \rightarrow ZZ \rightarrow l^+l^- jj$ channel

$h \rightarrow ZZ \rightarrow l^+l^- l^+l^-$



M_h > 600 GeV:

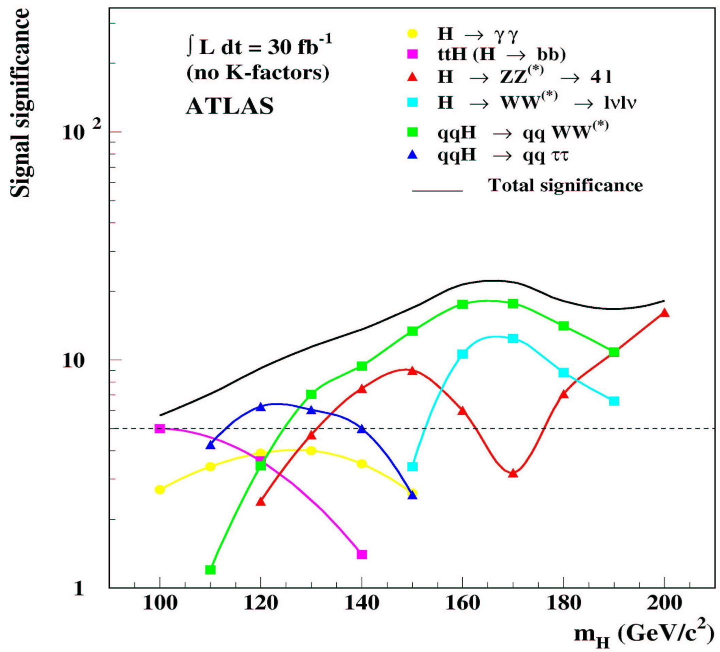
4 lepton channel statistically limited

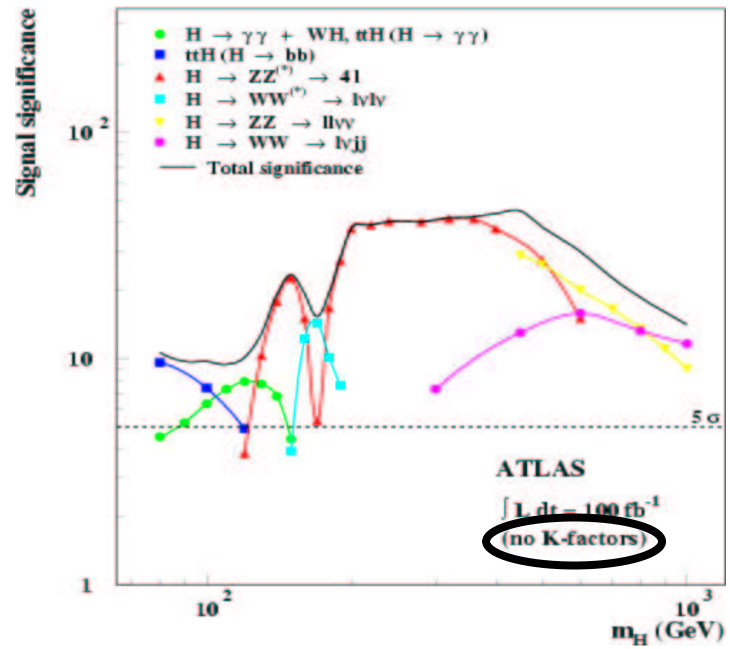
$h \rightarrow ZZ \rightarrow l^+l^- \nu\nu$

$h \rightarrow ZZ \rightarrow l^+l^- jj$, $h \rightarrow WW \rightarrow l\ \nu jj$

-150 times larger BR than 4l channel

If there is a light SM Higgs, we'll find it at the LHC





No holes in M_h coverage

Discovery happens early in the game

If we find a "Higgs-like" object, what then?

- We need to:
  - Measure Higgs couplings to fermions & gauge bosons
  - Measure Higgs spin/parity
  - Reconstruct Higgs potential
  - Is it the SM Higgs?
- Reminder: Many models have other signatures:
  - New gauge bosons (little Higgs)
  - Other new resonances (Extra D)
  - Scalar triplets (little Higgs, NMSSM)
  - Colored scalars (MSSM)
  - etc

Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

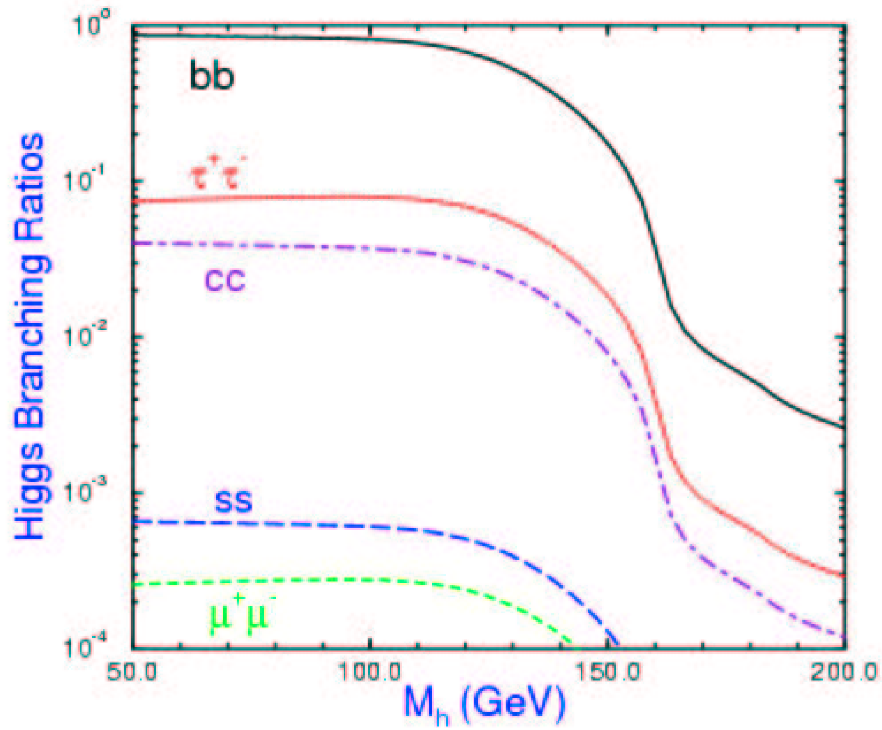
$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b^{\ 2}}{m_\tau^{\ 2}}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

- Measure self interactions

$$V = \frac{M_h^{\ 2}}{2}h + \frac{M_h^{\ 2}}{2v}h^3 + \frac{M_h^{\ 2}}{8v^2}h^4$$



Very hard at hadron collider

Measurements of Higgs couplings

- Ratios of couplings more precisely measured than absolute couplings
- LHC measures $\sigma(pp \rightarrow h)BR(h \rightarrow X) = \sigma(pp \rightarrow h)\Gamma(h \rightarrow X) / \Gamma_{tot}$

Vector Boson Fusion:

$X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma}$ from $qq \rightarrow qqh$, $h \rightarrow \gamma\gamma$

$X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma}$ from $qq \rightarrow qqh$, $h \rightarrow \tau^+\tau^-$

$X_W = \frac{\Gamma_W^{\ 2}}{\Gamma}$ from $qq \rightarrow qqh$, $h \rightarrow W^+W^-$

Gluon Fusion:

$Y_g = \frac{\Gamma_g \Gamma_\gamma}{\Gamma}$ from $gg \rightarrow h \rightarrow \gamma\gamma$

$Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma}$ from $gg \rightarrow h \rightarrow ZZ$

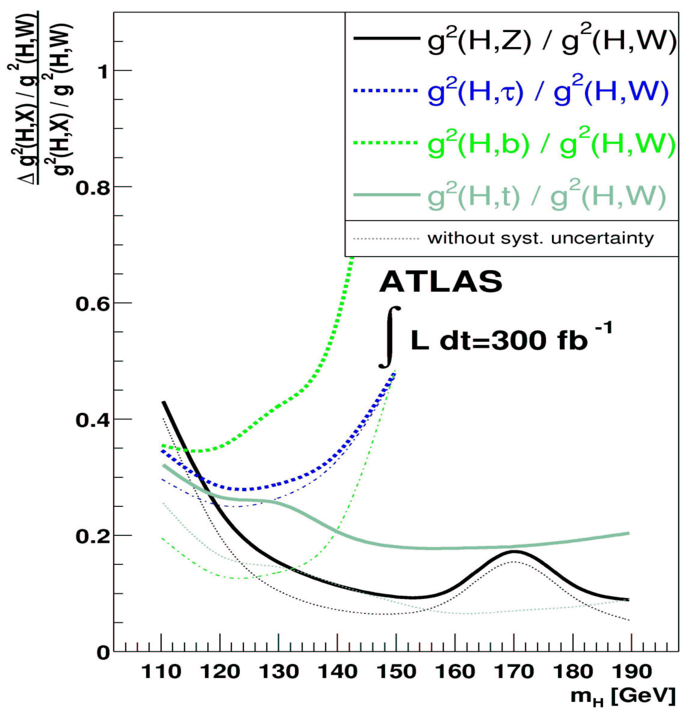
$Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma}$ from $gg \rightarrow h \rightarrow W^+W^-$

Ratios of X or Y's factor out Γ_W or Γ_g;
also PDF and σ uncertainties

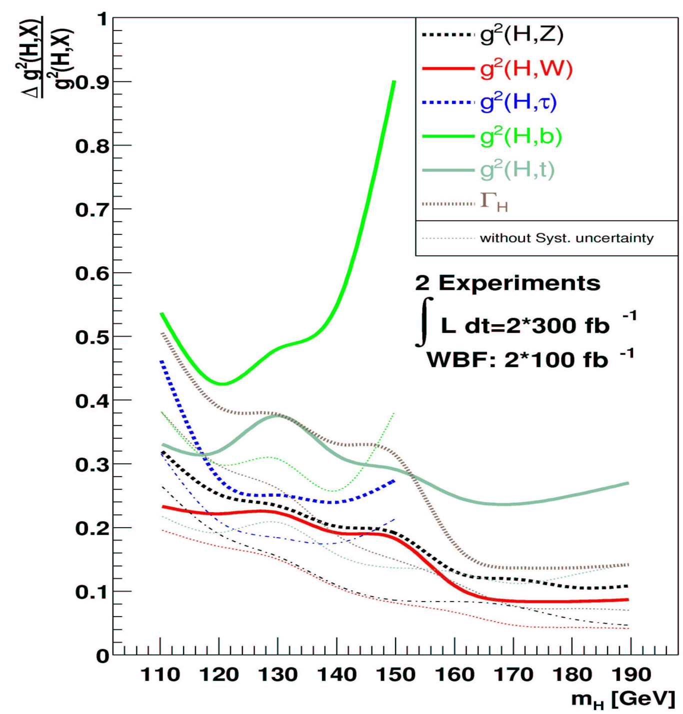
Belyaev & Reina, hep-ph/0205270

Absolute measurements of Higgs couplings

- ➢Ratios of couplings more precisely measured than absolute couplings
- ➢10-40% measurements of most couplings



Duhrssen, ATL-PHYS-2003-030

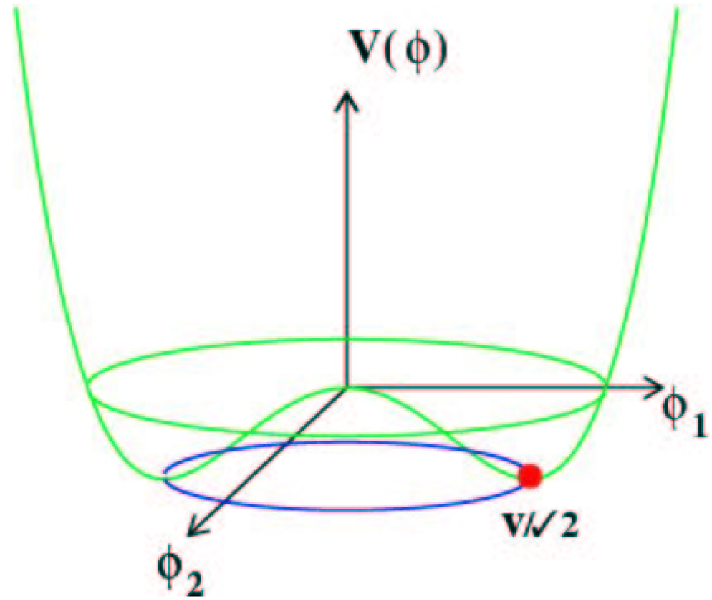


Duhrssen et al, hep-ph/0407190

Can we reconstruct the Higgs potential?

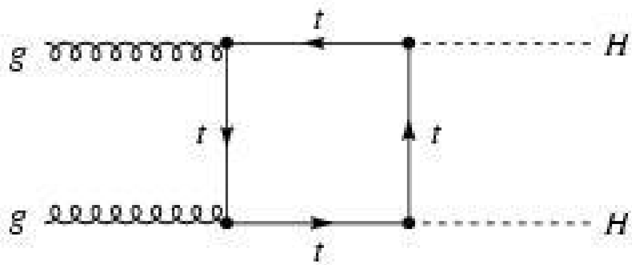
$$V = \frac{M_h^{\ 2}}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

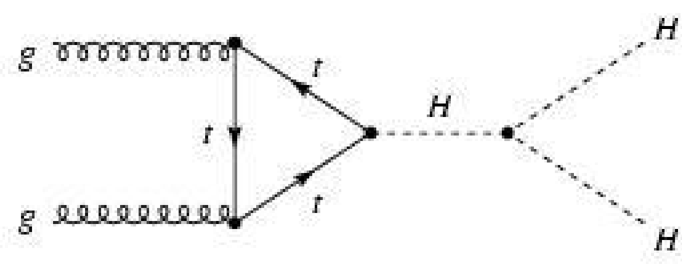
$$\boxed{SM : \lambda_3 = \lambda_4 = \frac{M_h^{\ 2}}{2v^2}}$$



- ➢Fundamental test of model!
- ➢We have no idea how to measure λ_4

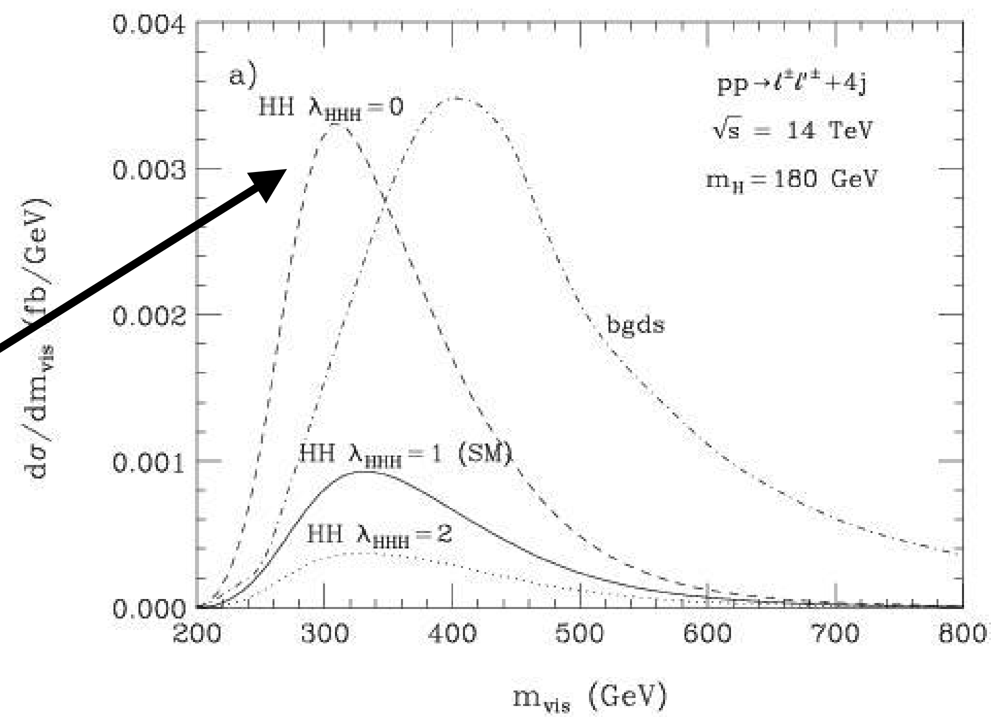
Reconstructing the Higgs potential





- λ_3 requires 2 Higgs production
- M_h<140 GeV, $h \rightarrow b\bar{b}b\bar{b}$
- Overwhelming QCD background
- Easier at higher M_h

Can determine whether λ_3=0 at 95% cl with 300 fb^{-1} for 150<M_h<200 GeV



Baur, Plehn & Rainwater, hep-ph/0304015

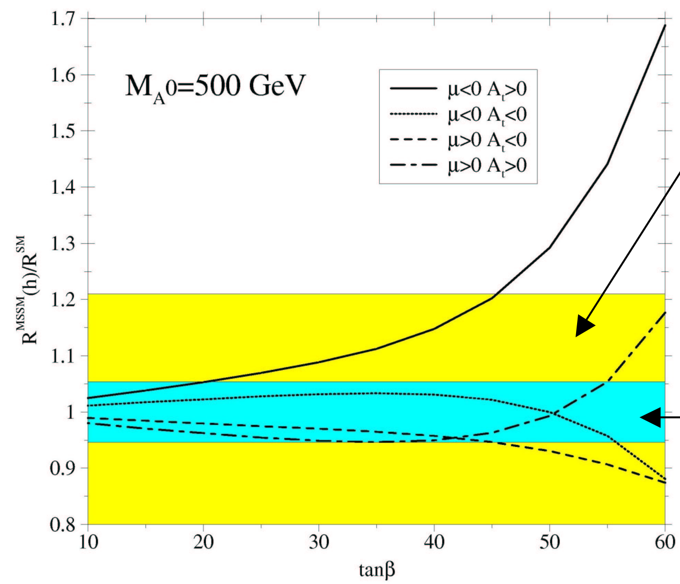
Higgs measurements test model!

- Supersymmetric models are our favorite comparison
  - See Peskin's lectures
- SUSY Higgs sector
  - At least 2 Higgs doublets
    - SM masses from $L = -g_d \overline{Q}_L \Phi d_R - g_u \overline{Q}_L \Phi^c u_R + h.c.$
    - Φ^c term not allowed in SUSY models: Need second Higgs doublet with opposite hypercharge
  - 5 physical Higgs: $h^0, H^0, A^0, H^{\pm}$
  - General 2 Higgs doublet potential has 6 couplings and a phase
  - SUSY Higgs potential has only 2 couplings
  - Take these to be M_A and $\tan\beta$
    - At tree level everything is predicted
    - Lightest Higgs mass has upper limit

How well do we need Higgs couplings?

- MSSM example:

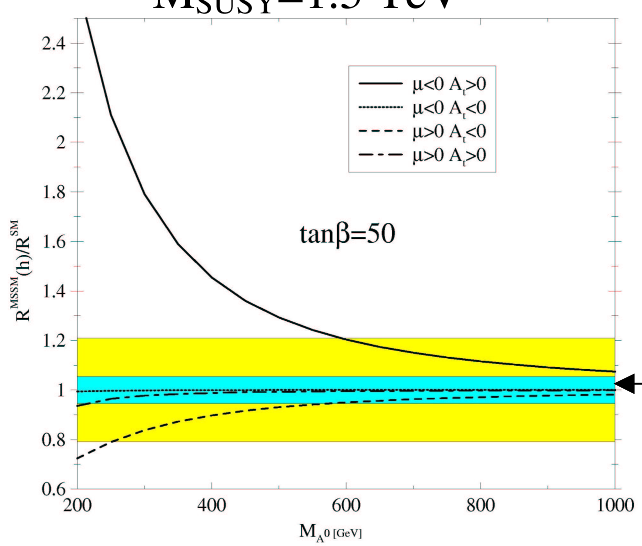
$$R = \frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)}$$



21% deviation from SM

5.4% deviation from SM

M_{SUSY}=1.5 TeV



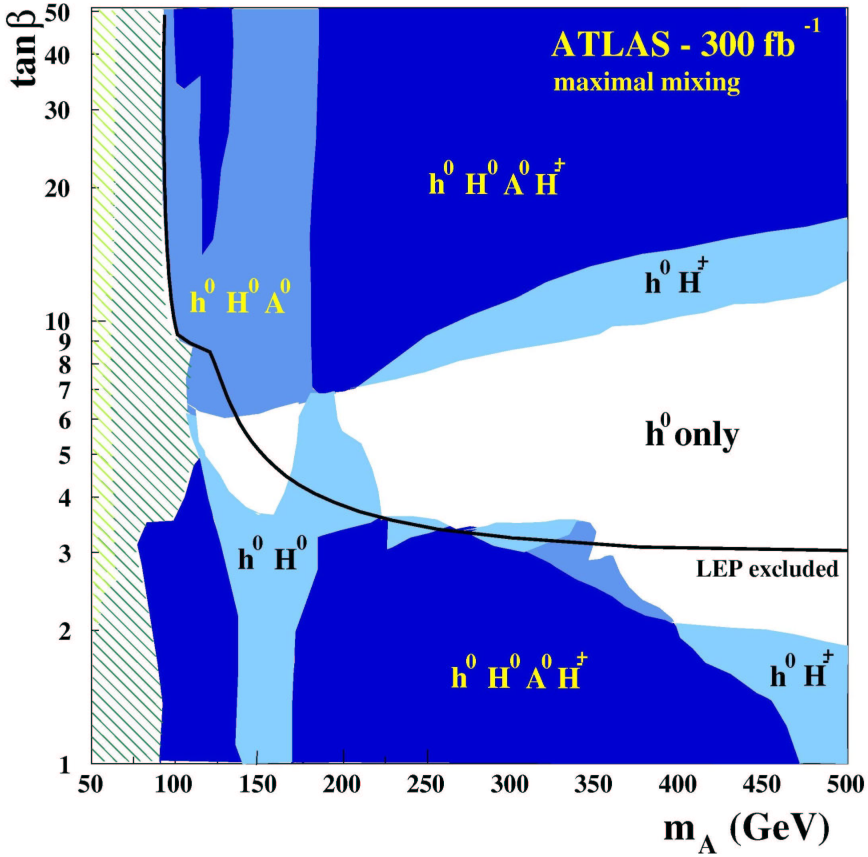
Note rapid approach to SM limit

Guasch, Hollik, Penaranda, hep-ph/0307012

MSSM discovery

- For large fraction of M_A-tanβ space, more than one Higgs boson is observable
- For $M_A \rightarrow \infty$, MSSM becomes SM-like
- Plot shows regions where Higgs particles can be observed with > 5σ

Need to observe multiple Higgs bosons and measure their couplings



What's wrong with the SM with a light Higgs?

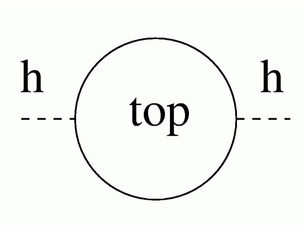
- Higgs mass is quadratically sensitive to physics at higher scales
  - SM doesn't include gravity, so we know there must be something more
- SM doesn't explain why $M_W << M_{pl}$: The Hierarchy problem
  - Loop corrections to propagators give corrections to particle masses
  - Consider electron self-energy in QED

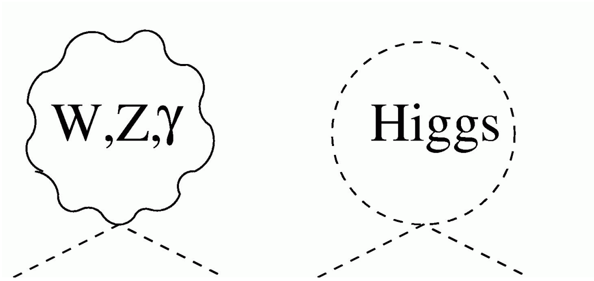
$$\Sigma^{ee} \approx m_e \int^{\Lambda} \frac{dk}{k} \approx 2\frac{\alpha}{\pi} m_e \ln\left(\frac{\Lambda}{m_e}\right)$$

  - Numerically small: Chiral symmetry in limit $m_e \rightarrow o$

Light Scalars are unnatural

- Higgs mass grows with scale of new physics, Λ
- No additional symmetry for M_h=0, no protection from large corrections





$$\delta M_h^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_h^2 - 12M_t^2\right)$$

$$= -\left(\frac{\Lambda}{0.7\ \text{TeV}}\,200\ \text{GeV}\right)^2$$

$M_h \leq 200$ GeV requires large cancellations

Interacting Scalar Field Theories don't make sense at all energy scales

- SM based on $V(\phi)= M_h^2\phi^2+ \lambda\phi^4$
- $\lambda(\mu)$ related to higher scale Λ by:

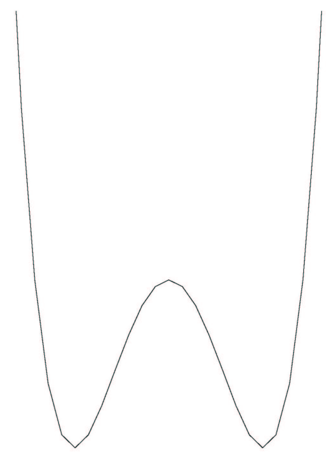
$$\boxed{\frac{1}{\lambda(\mu)}=\frac{1}{\lambda(\Lambda)}+\frac{3}{2\pi^2}\log\left(\frac{\Lambda}{\mu}\right)}$$

- Require $\lambda(\Lambda) > 0$ (ie $V(\phi)$ doesn't go to $-\infty$)

$$\boxed{\frac{1}{\lambda(\mu)}\geq\frac{3}{2\pi^2}\log\left(\frac{\Lambda}{\mu}\right)}$$

- Upper bound on $\lambda(\mu)$ and hence on M_h

$$\boxed{M_h^2<\frac{4\pi^2 v^2}{3\log(\Lambda/v)}}$$



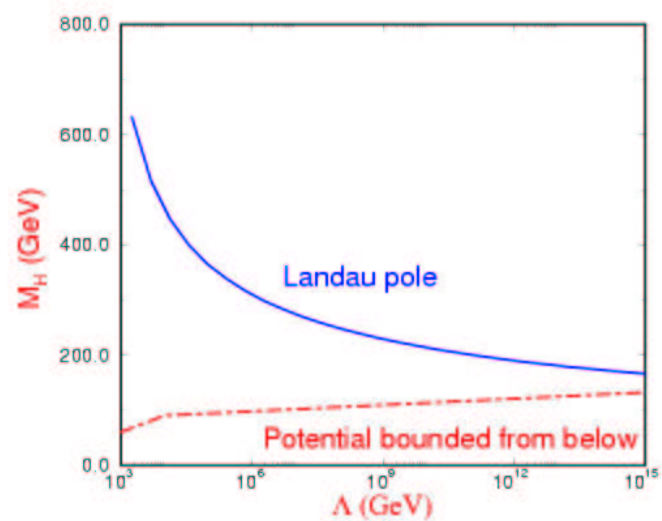
On the other hand….

- If we take the limit $\Lambda \to \infty$, with μ fixed, then $\lambda(\mu)$ is forced to 0
  - We say the theory is ***trivial***
- This gives lower bound on M_h

$$\boxed{M_h > \Lambda e^{\left(3M_h^2/4\pi^2 v^2\right)}}$$

- If SM makes sense to $M_{GUT}=10^{16}$ GeV, then

$$\boxed{130 GeV \leq M_h \leq 175 GeV}$$



For any M_h, there is a maximum scale, Λ, at which the theory makes sense

Corollary: SM must be an effective low energy theory

Conclusions

- If a SM Higgs exists, the LHC will find it
- But there will still be questions…..